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Rowden et al.

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(54) **ROBUST LOW INDUCTANCE POWER
MODULE PACKAGE**

(58) **Field of Classification Search**
CPC . H01L 2224/48237; H01L 2224/48257; H01L
23/495; H01L 23/492;

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(Continued)

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(57) **ABSTRACT**

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H01L 23/49 (2006.01)
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H01L 23/50 (2006.01)
H01L 25/00 (2006.01)
H01L 25/18 (2006.01)
H01L 25/07 (2006.01)

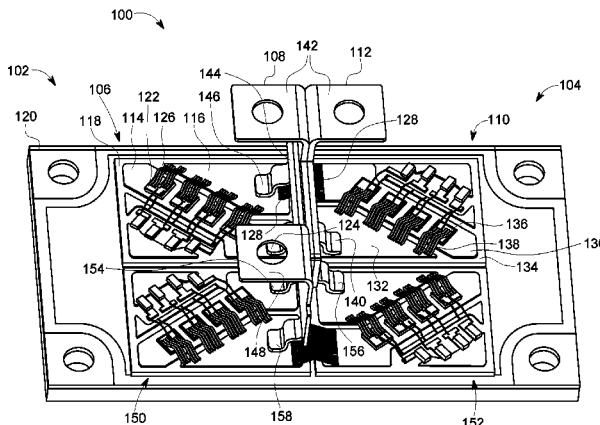
A method and system for a power module is provided. The
power module includes a first substrate including a first
conductive substrate having a first plurality of power semi-
conductor switches arranged thereon, and at least one second
conductive substrate electrically coupled to the first conduc-
tive substrate. A first terminal is electrically coupled to the
first conductive substrate. The power module also includes
a second substrate including a third conductive substrate
having a second plurality of power semiconductor switches
arranged thereon, and at least one fourth conductive sub-
strate electrically coupled to the third conductive substrate.
The third conductive substrate is electrically coupled to the
second conductive substrate. A second terminal is electri-
cally coupled to the fourth conductive substrate.

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(2013.01); **H01L 23/49** (2013.01); **H01L**
23/492 (2013.01);

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20 Claims, 13 Drawing Sheets



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H01L 25/072 (2013.01); **H01L 25/18**
 (2013.01); **H01L 25/50** (2013.01); **H01L**
2224/48245 (2013.01)

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 23/49562; H01L 23/142; H01L 24/48;
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 2224/48245; H01L 23/50; H01L 23/49;
 H01L 2924/00; H01L 2224/48091
 See application file for complete search history.

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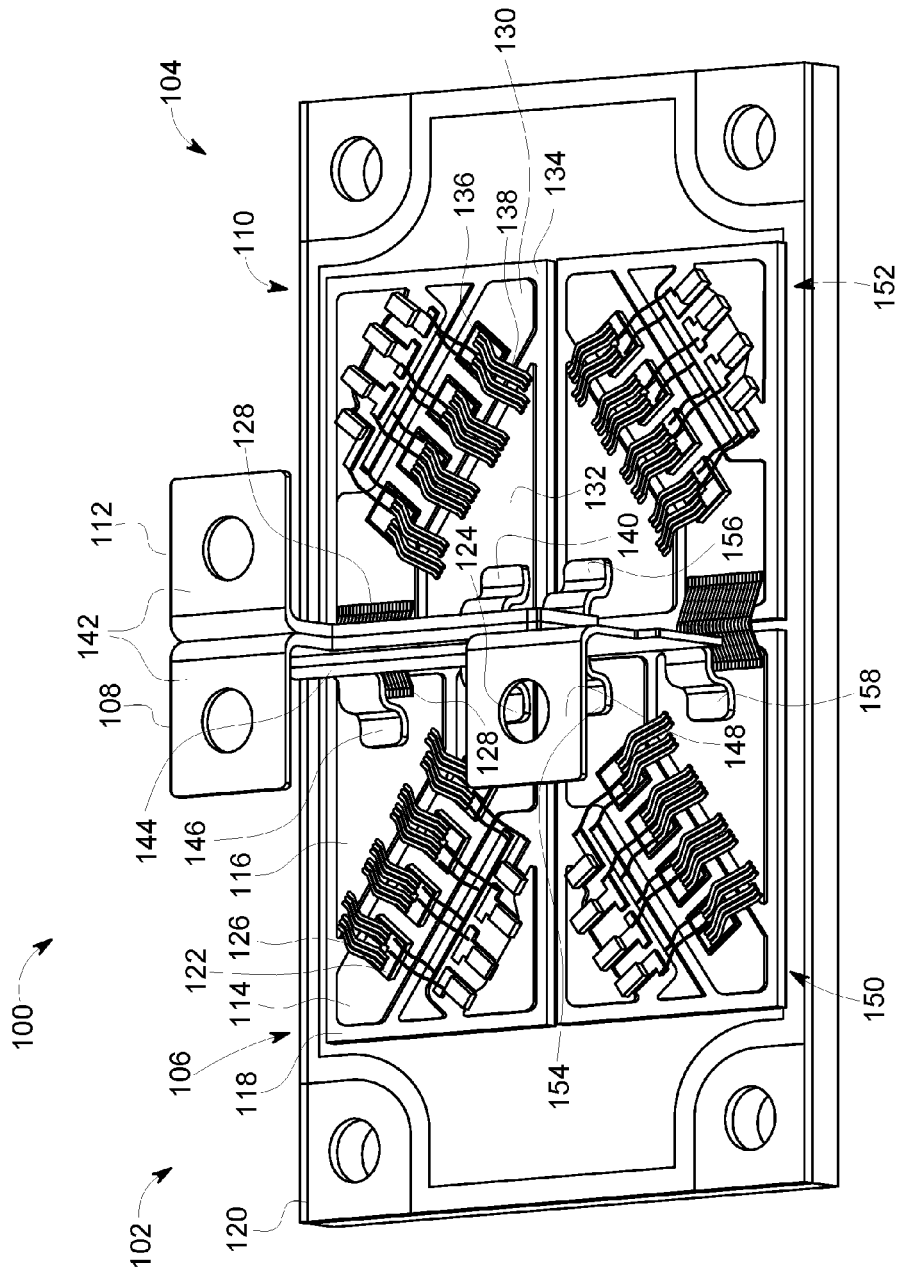


FIG. 1

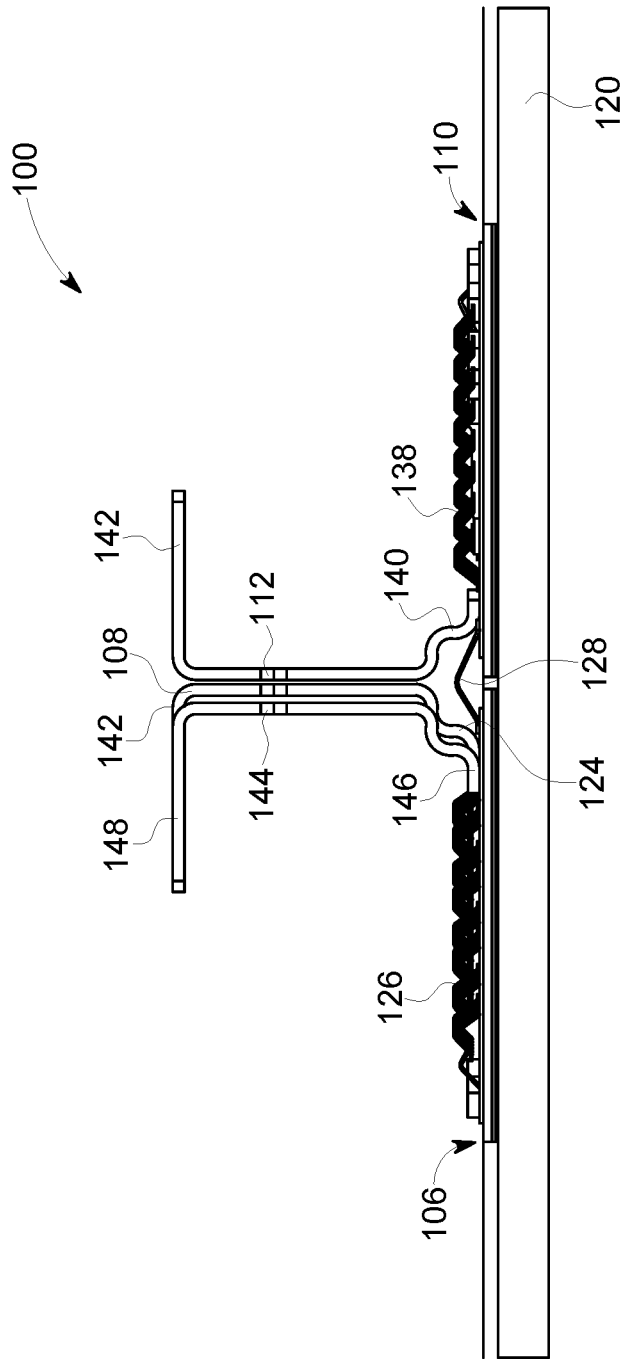


FIG. 3

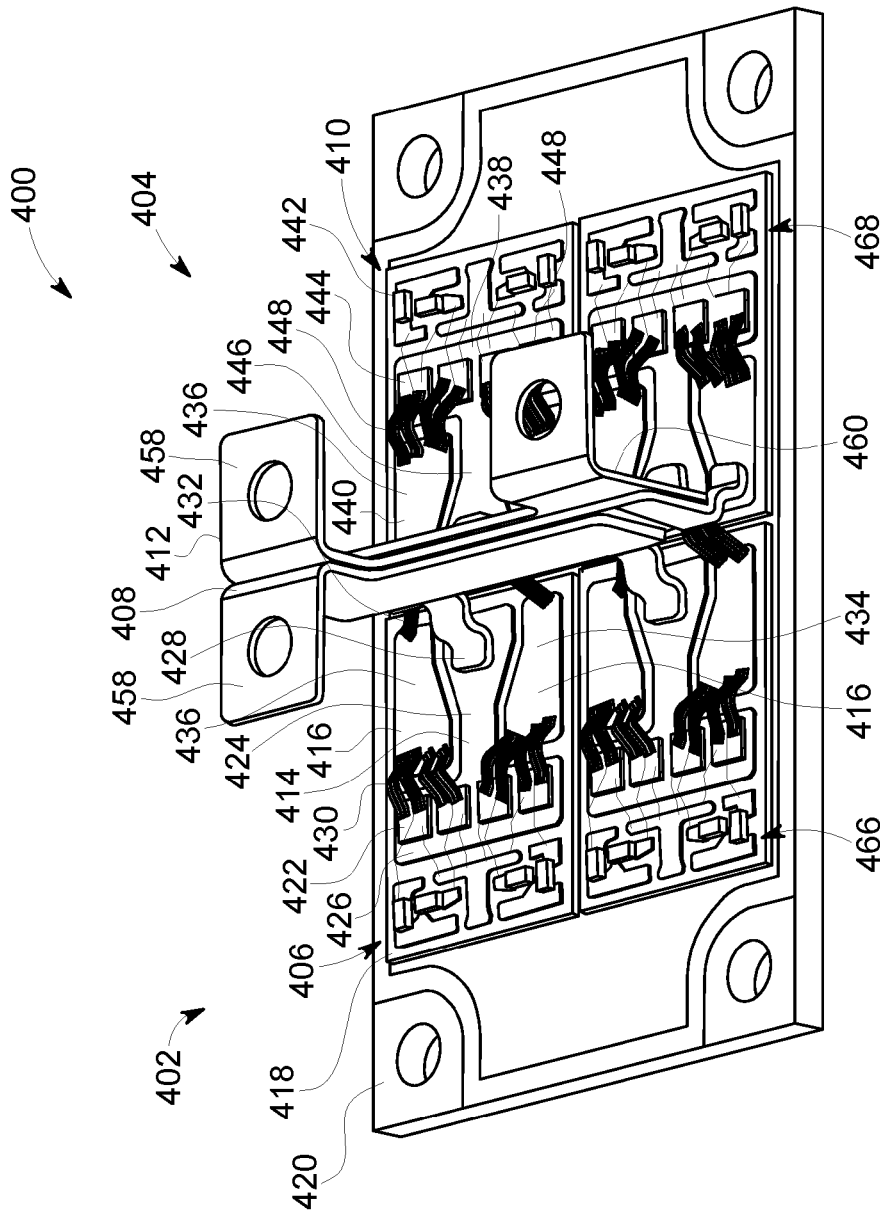


FIG. 4

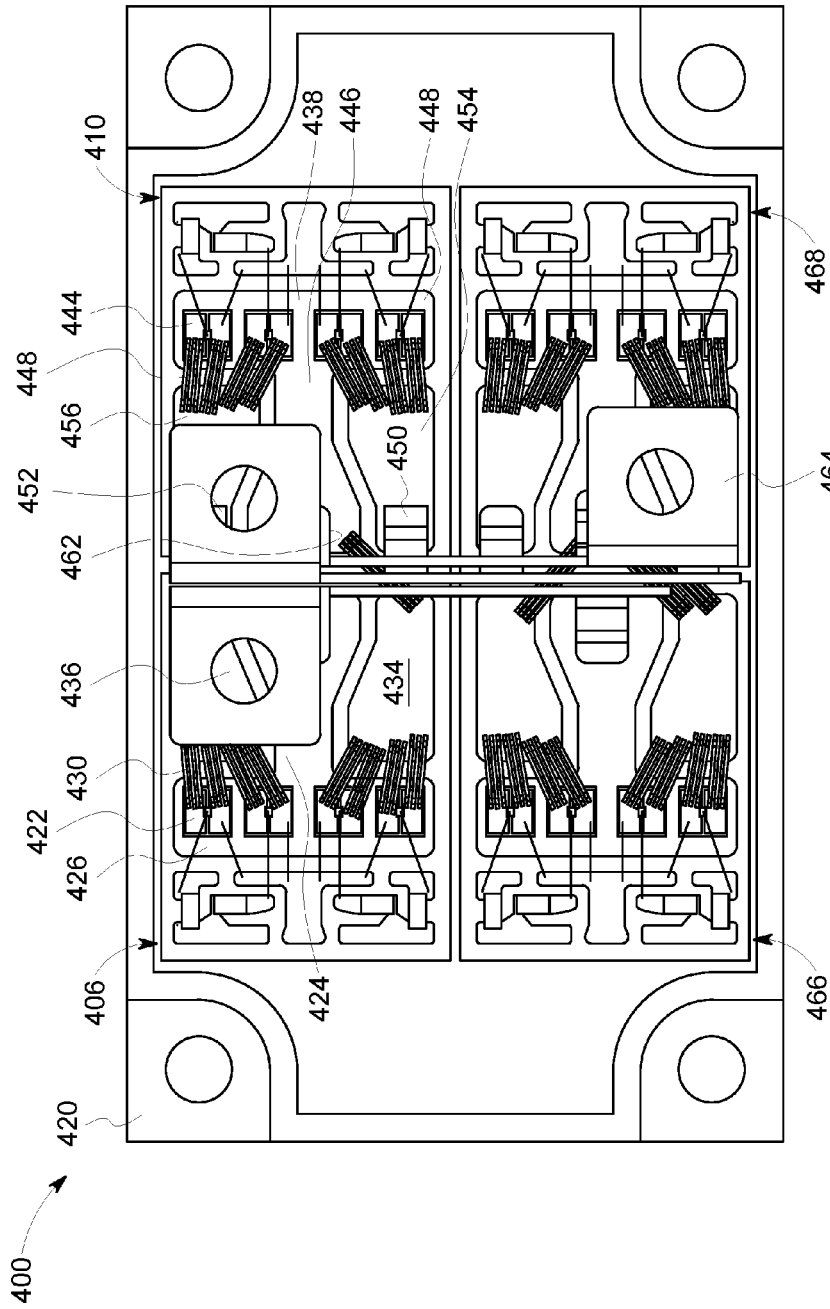


FIG. 5

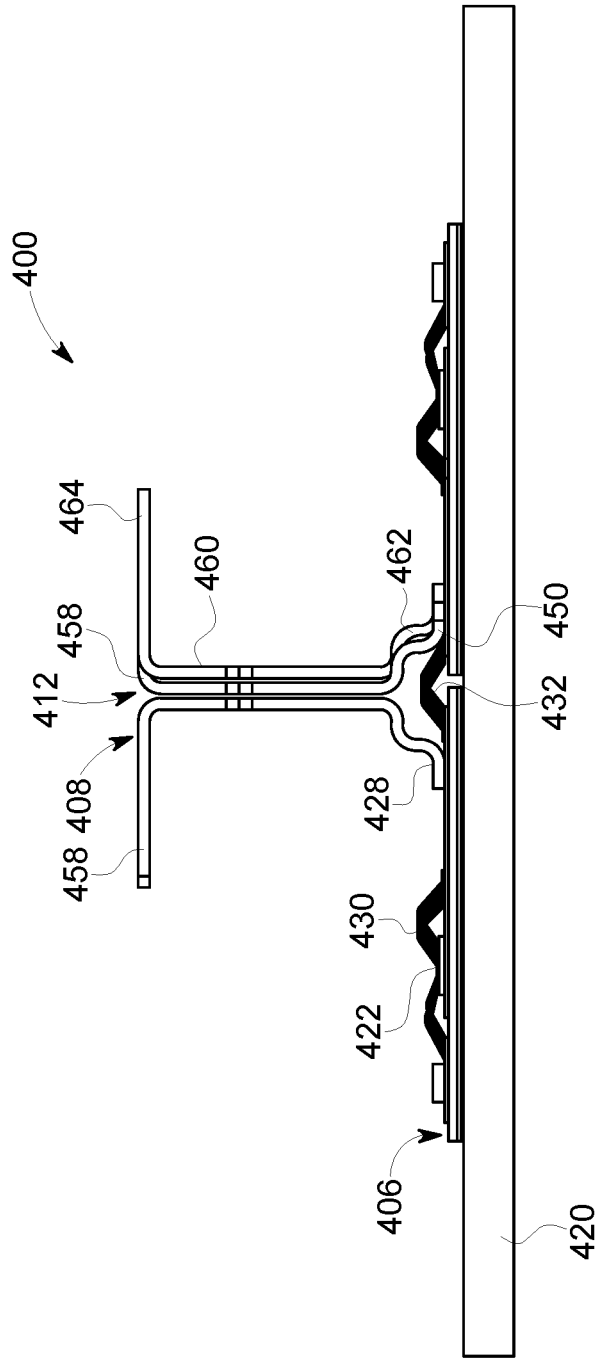


FIG. 6

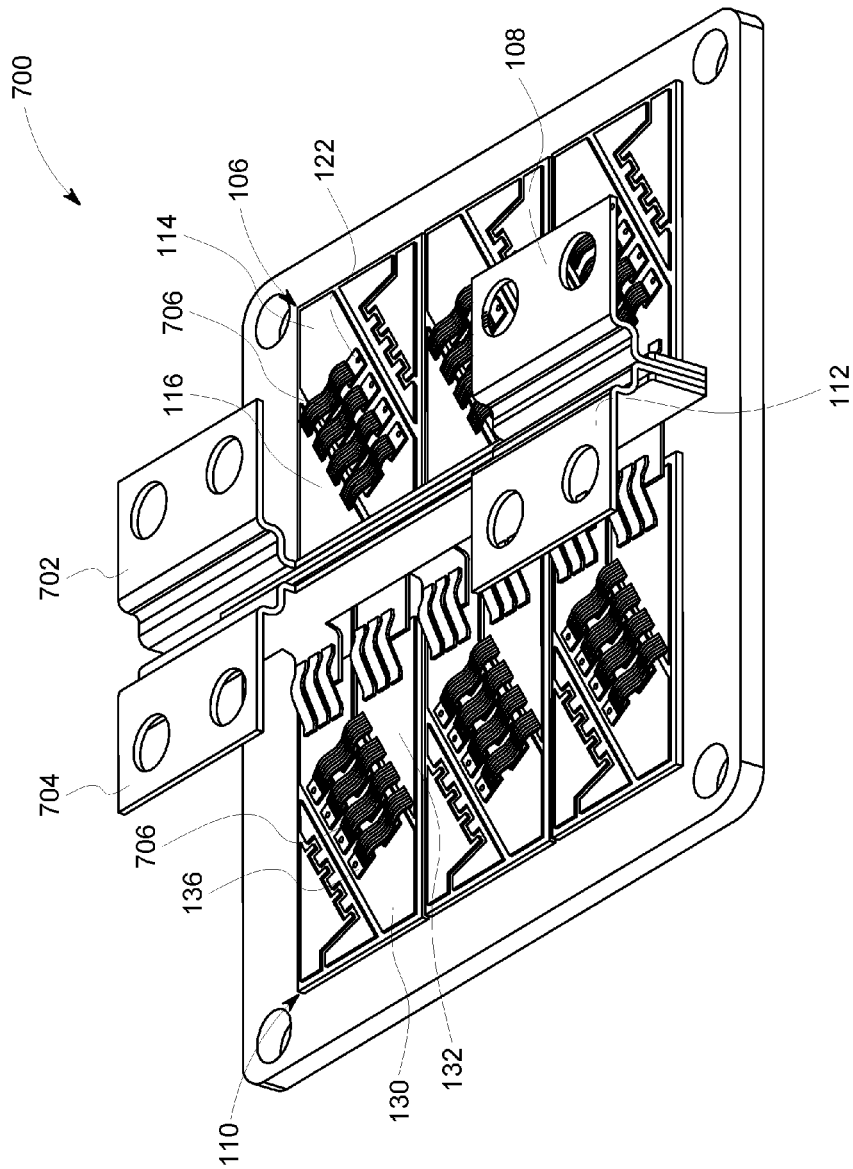


FIG. 7

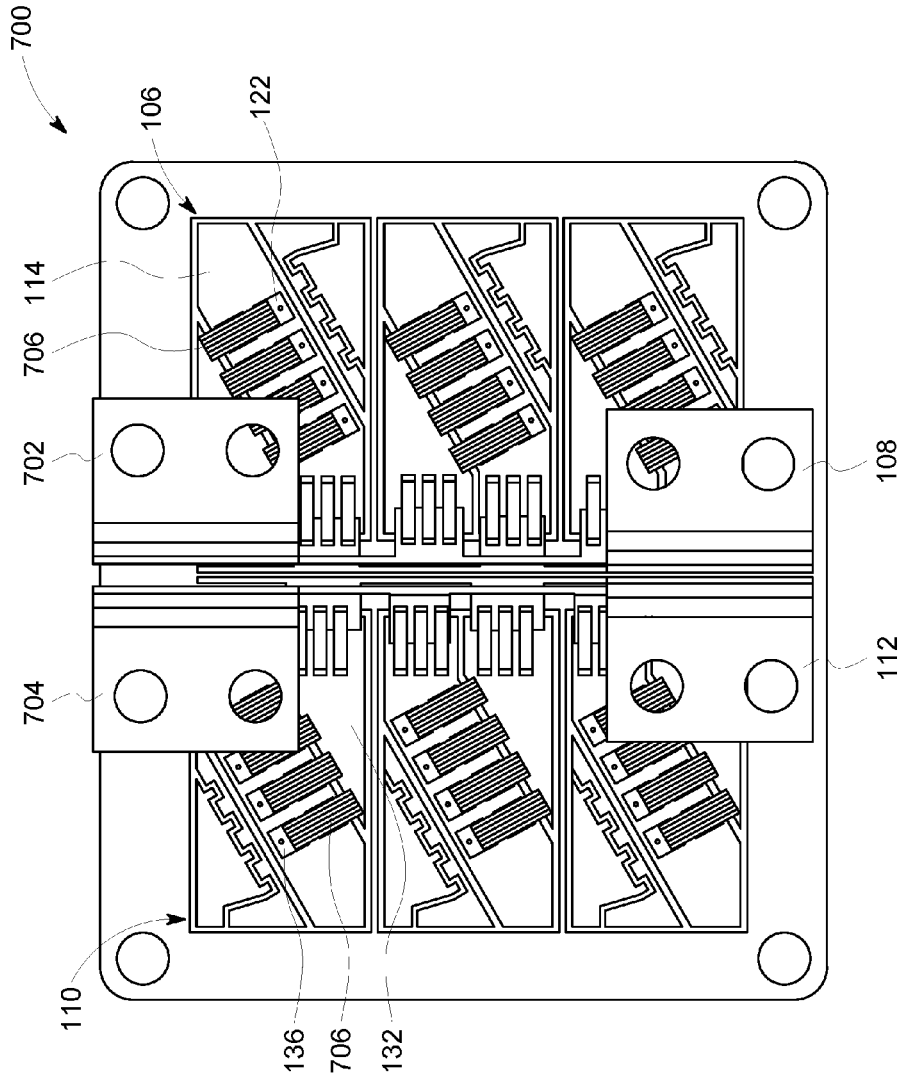


FIG. 8

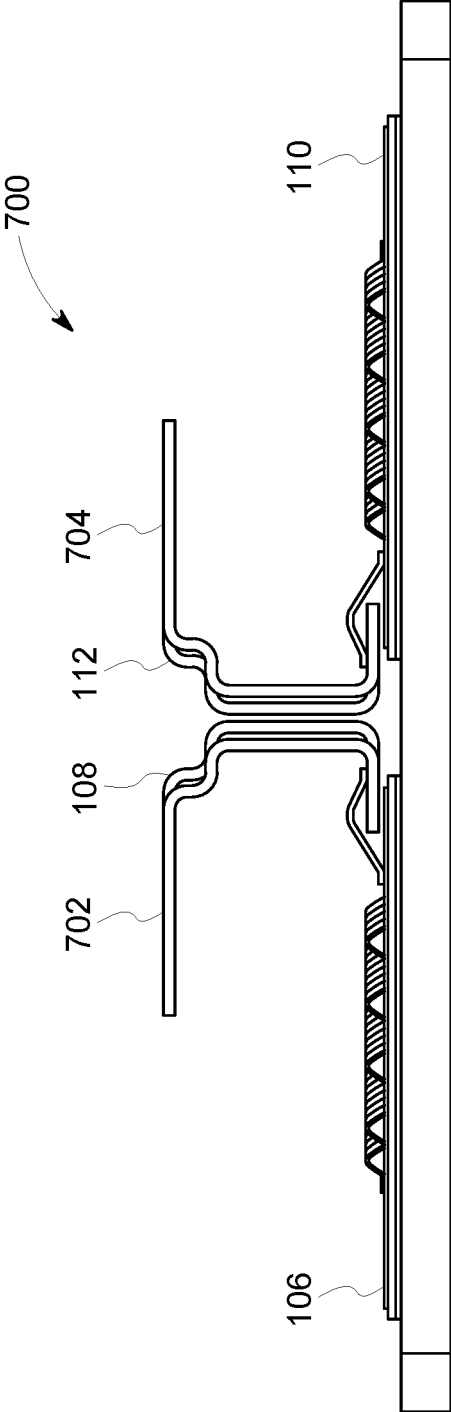


FIG. 9

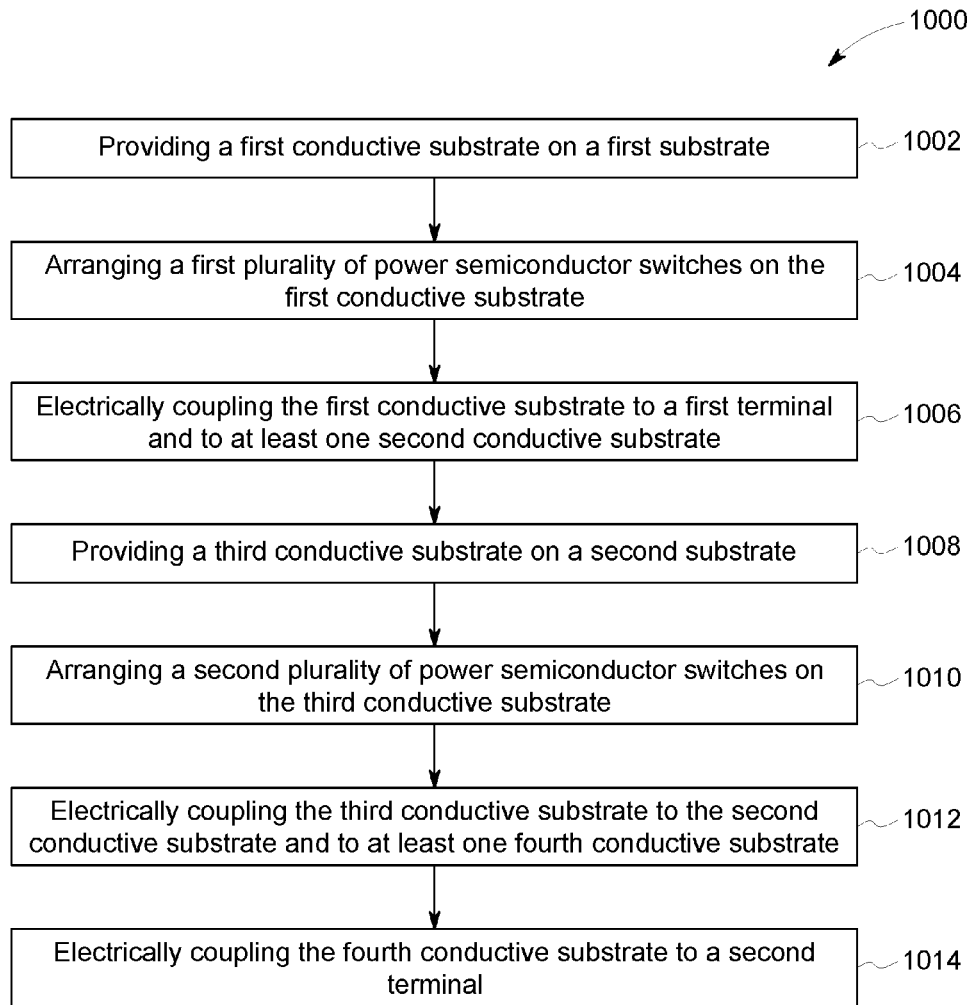


FIG. 10

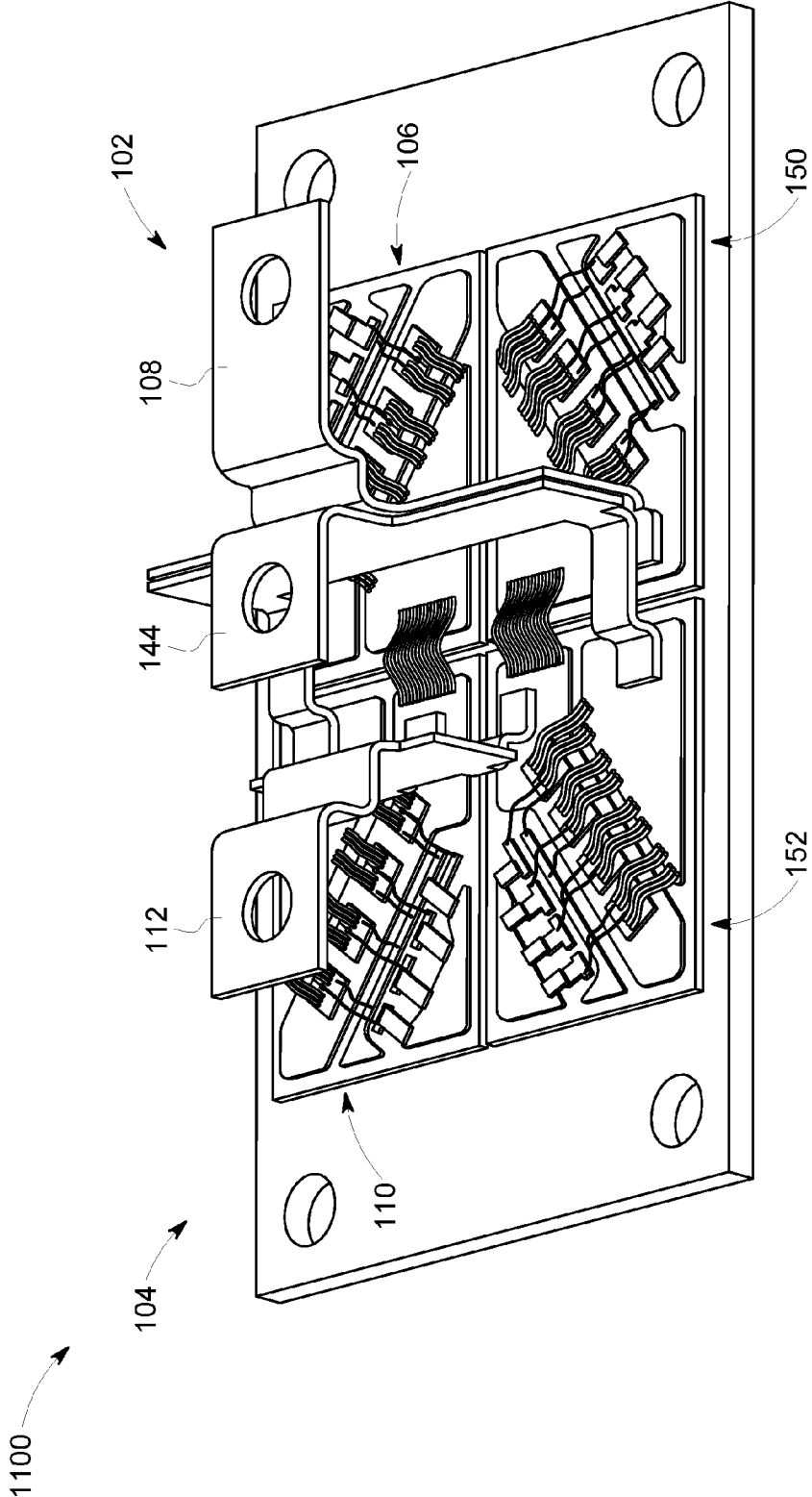


FIG. 11

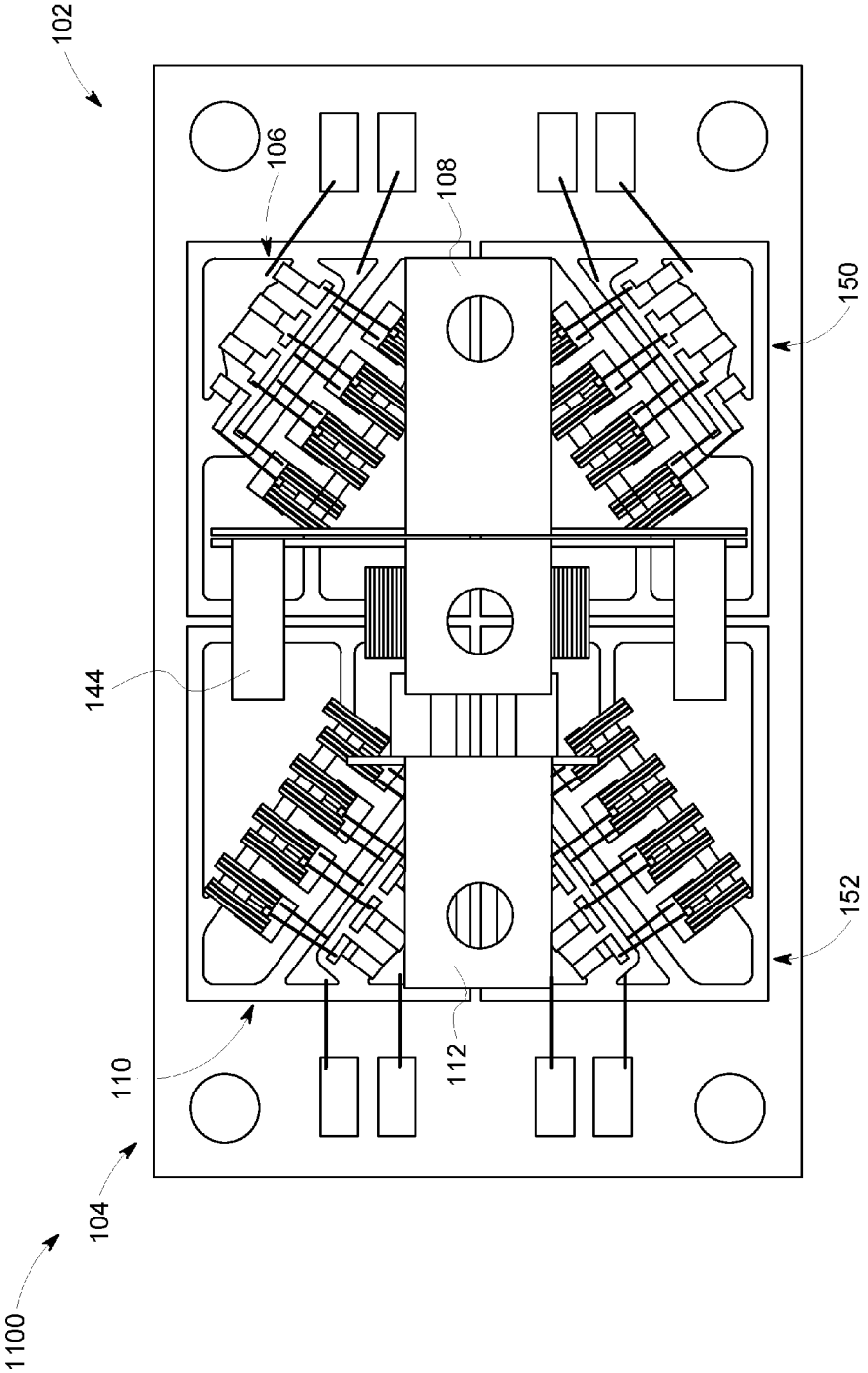


FIG. 12

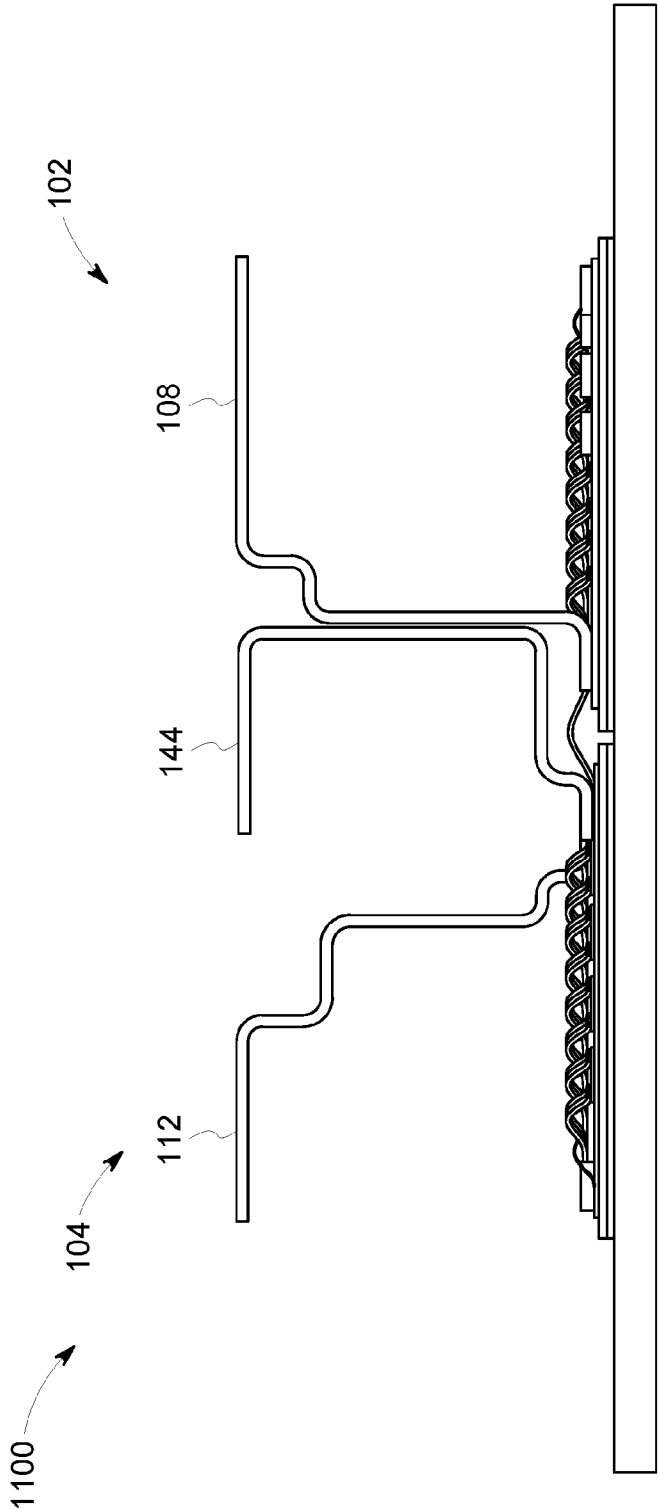


FIG. 13

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ROBUST LOW INDUCTANCE POWER MODULE PACKAGE

BACKGROUND

The field of the disclosure relates generally to power switching module assemblies and, more particularly, to power switching module assembly structures that provide low circuit inductance.

The field of the disclosure relates generally to power switching module assemblies and, more particularly, to power switching module assembly structures that provide low circuit inductance.

At least some known semiconductor power module packages route signals either through a power substrate or through metal traces in a wall geometry. For the power substrate, the signal paths are typically direct bond or active metal brazed copper or aluminum on a ceramic substrate which are single layer and require that the traces be adjacent to one another on a planar surface. The semiconductor devices are then wire, ribbon, or planar interconnect bonded to the planar metal traces which run across the module and are wire, ribbon, or planar interconnect bonded to the output terminals.

To improve the efficiency and the reliability of power semiconductor devices, the surrounding packaging connecting the power devices to the power system must introduce minimal parasitic inductance, which may contribute to power system losses or may have a detrimental impact on the capability of the device either electrically, thermally, or mechanically. For power modules, the interconnects from devices are typically implemented with wire, ribbon, or planar interconnect bonding to copper traces routed on insulating substrates called direct bond copper (DBC). For power modules, the main or commutation power loop is the path of primary concern with current flowing between the positive and negative DC terminals.

BRIEF DESCRIPTION

In one embodiment, a power module is provided. The power module includes a first substrate including a first conductive substrate having a first plurality of power semiconductor switches arranged thereon, and at least one second conductive substrate electrically coupled to the first conductive substrate. A first terminal is electrically coupled to the first conductive substrate. The power module also includes a second substrate including a third conductive substrate having a second plurality of power semiconductor switches arranged thereon, and at least one fourth conductive substrate electrically coupled to the third conductive substrate. The third conductive substrate is electrically coupled to the second conductive substrate. A second terminal is electrically coupled to the fourth conductive substrate.

In another embodiment, a method of forming a power module is provided. The method includes providing a first conductive substrate on a first substrate, arranging a first plurality of power semiconductor switches on the first conductive substrate, and electrically coupling the first conductive substrate to a first terminal and to at least one second conductive substrate. The method also includes providing a third conductive substrate on a second substrate, arranging a second plurality of power semiconductor switches on the third conductive substrate, and electrically coupling the third conductive substrate to the second conductive substrate and to at least one fourth conductive substrate. The method

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further includes electrically coupling the fourth conductive substrate to a second terminal.

DRAWINGS

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These and other features, aspects, and advantages of the present disclosure will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

10 FIG. 1 is a perspective view of an exemplary power module;

FIG. 2 is a top view of the power module shown in FIG. 1;

15 FIG. 3 is a side view of the power module shown in FIGS. 1 and 2;

FIG. 4 is a perspective view of an exemplary power module;

20 FIG. 5 is a top view of the power module shown in FIG. 4;

FIG. 6 is a side view of the power module shown in FIGS. 4 and 5; and

FIG. 7 is a perspective view of an exemplary power module.

25 FIG. 8 is a top view of the power module shown in FIG. 7.

FIG. 9 is a side view of the power module shown in FIGS. 7 and 8; and

30 FIG. 10 is a flow chart of an exemplary method of forming the power modules shown in FIGS. 1-3, 4-6, and 7-9 in accordance with an exemplary embodiment of the present disclosure.

FIG. 11 is a perspective view of an exemplary power module.

35 FIG. 12 is a top view of the power module shown in FIG. 11.

FIG. 13 is a side view of the power module shown in FIGS. 11 and 12.

40 Unless otherwise indicated, the drawings provided herein are meant to illustrate features of embodiments of this disclosure. These features are believed to be applicable in a wide variety of systems including one or more embodiments of this disclosure. As such, the drawings are not meant to include all conventional features known by those of ordinary skill in the art to be required for the practice of the embodiments disclosed herein.

DETAILED DESCRIPTION

50 In the following specification and the claims, reference will be made to a number of terms, which shall be defined to have the following meanings.

The singular forms “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise.

55 “Optional” or “optionally” means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where the event occurs and instances where it does not.

60 Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about”, “approximately”, and “substantially”, are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the

value. Here and throughout the specification and claims, range limitations may be combined and/or interchanged, such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise.

FIG. 1 is a perspective view of an exemplary power module 100. FIG. 2 is a top view of power module 100. FIG. 3 is a side view of power module 100. In the exemplary embodiment, power module 100 includes a first side 102 and a second side 104. First side 102 includes a first substrate 106 electrically coupled to a first terminal 108. Second side 104 includes a second substrate 110 electrically coupled to a second terminal 112.

First substrate 106 includes a first conductive substrate 114 and a second conductive substrate 116. First and second conductive substrates 114, 116 are patterned copper layers that are disposed on a dielectric layer 118. Dielectric layer 118 may be made of ceramic material, such as alumina (Al₂O₃), aluminum nitride (AlN), silicon nitride (Si₃N₄) and like. First substrate 106, including first and second conductive substrates 114, 116 coupled to dielectric layer 118 forms a power electronic substrate, such as a direct bonded copper (DBC) substrate. First substrate 106 is disposed on a substantially planar baseplate 120.

First conductive substrate 114 includes a first plurality of power semiconductor switches 122 arranged thereon. For example, in the exemplary embodiment, the first plurality of power semiconductor switches 122 includes metal-oxide semiconductor field-effect transistors (MOSFET). Alternatively, the first plurality of power semiconductor switches 122 may include insulated gate bipolar transistors (IGBT), junction gate field-effect transistors (JFET), bipolar junction transistors (BJT). In addition to the aforementioned power switches, the substrate may also include anti-parallel rectifier diodes, such as PiN diode, Schottky Barrier Diode (SBD), or Junction Barrier Schottky (JBS) diode. The first plurality of power semiconductor switches 122 may be formed of semiconducting material, such as, for example, silicon, silicon carbide (SiC), Aluminum nitride (AlN), Gallium nitride (GaN), or Boron nitride (BN). In the exemplary embodiment, first conductive substrate 114 includes four power semiconductor switches 122 arranged thereon; however, first conductive substrate 114 may include any number of power semiconductor switches that enables power module 100 to function as described herein.

Each of the first plurality of power semiconductor switches 122 includes a drain terminal electrically coupled to first terminal 108 via first conductive substrate 114. That is, each of the first plurality of power semiconductor switches 122 has the drain connection on a bottom side of the switch. First terminal 108 is either soldered or ultrasonically welded to first conductive substrate 114 to form the electrical connection therebetween. First terminal 108 includes a first foot 124 extending therefrom that electrically couples it to first conductive substrate 114.

Each of the first plurality of power semiconductor switches 122 also includes a source terminal electrically coupled to second conductive substrate 116 using a first wire bond 126. That is, each of the first plurality of power semiconductor switches 122 has the source connection on a top side of the switch. First wire bond 126 is coupled to the top side of the switch to couple the source terminal to second conductive substrate 116. Thus, first conductive substrate 114 is electrically coupled to second conductive substrate 116 via the first plurality of power semiconductor switches 122 and first wire bonds 126.

Second conductive substrate 116 is electrically coupled to first wire bonds 126 to form the electrical connection with first conductive substrate 114. Second conductive substrate 116 is also electrically coupled to a second wire bond 128 to form an electrical connection with second side 104 of power module 100.

Current flowing from first terminal 108 flows through first foot 124 into first conductive substrate 114, through the drain terminal of each of the first plurality of power semiconductor switches 122, then through the source terminal of each of the first plurality of power semiconductor switches 122, through first wire bonds 126, and into second conductive substrate 116.

Second substrate 110 includes a third conductive substrate 130 and a fourth conductive substrate 132. Third and fourth conductive substrates 130, 132 are patterned copper layers that are disposed on a dielectric layer 134. Dielectric layer 134 may be made of ceramic material, such as alumina (Al₂O₃), aluminum nitride (AlN), silicon nitride (Si₃N₄) and like. Second substrate 110, including third and fourth conductive substrates 130, 132 coupled to dielectric layer 134 forms a power electronic substrate, such as a direct bonded copper (DBC) substrate. Second substrate 110 is disposed on substantially planar baseplate 120.

Third conductive substrate 130 includes a second plurality of power semiconductor switches 136 arranged thereon. For example, in the exemplary embodiment, the second plurality of power semiconductor switches 136 includes metal-oxide semiconductor field-effect transistors (MOSFET). Alternatively, the second plurality of power semiconductor switches 136 may include insulated gate bipolar transistors (IGBT), junction gate field-effect transistors (JFET), or bipolar junction transistors (BJT). In addition to the aforementioned power switches, the substrate may also include anti-parallel rectifier diodes, such as PiN diode, Schottky Barrier Diode (SBD), or Junction Barrier Schottky (JBS) diode. The second plurality of power semiconductor switches 136 may be formed of semiconducting material, such as, for example, silicon carbide (SiC), Aluminum nitride (AlN), Gallium nitride (GaN), or Boron nitride (BN). In the exemplary embodiment, third conductive substrate 130 includes four power semiconductor switches 136 arranged thereon; however, third conductive substrate 130 may include any number of power semiconductor switches that enables power module 100 to function as described herein.

Each of the second plurality of power semiconductor switches 136 includes a drain terminal electrically coupled to second conductive substrate 116 via third conductive substrate 130. That is, each of the second plurality of power semiconductor switches 136 has the drain connection on a bottom side of the switch. The electrical connection of the drain terminal to third conductive substrate 130 enables each of the second plurality of power semiconductor switches 136 to receive current flowing from second conductive substrate 116 to third conductive substrate 130 via second wire bond 128.

Each of the second plurality of power semiconductor switches 136 also includes a source terminal electrically coupled to fourth conductive substrate 132 using a third wire bond 138. That is, each of the second plurality of power semiconductor switches 136 has the source connection on a top side of the switch. Third wire bond 138 is coupled to the top side of the switch to couple the source terminal to fourth conductive substrate 132. Thus, fourth conductive substrate 132 is electrically coupled to third conductive substrate 130 via the second plurality of power semiconductor switches 136 and third wire bonds 138.

Fourth conductive substrate **132** is electrically coupled to third conductive substrate **130** as well as to second terminal **112**. Second terminal **112** is either soldered or ultrasonically welded to fourth conductive substrate **132** to form the electrical connection therebetween. Second terminal **112** includes a first foot **140** extending therefrom that electrically couples it to fourth conductive substrate **132**.

Current flowing from second conductive substrate **116** flows through second wire bond **128** into third conductive substrate **130**, through the drain terminal of each of the second plurality of power semiconductor switches **136**, then through the source terminal of each of the second plurality of power semiconductor switches **136**, through third wire bonds **138** into fourth conductive substrate **132**, and into second terminal via first foot **140**.

In the exemplary embodiment, first terminal **108** is a positive DC terminal and second terminal **112** is a negative DC terminal. First terminal **108** and second terminal **112** are configured to be coupled to positive and negative external DC busbars (not shown), respectively. The “positive” and “negative” DC terminals and/or external DC busbars are at different electric potentials relative to one another during operation, but are not restricted to a specific polarity. In the exemplary embodiment, first terminal **108** and second terminal **112** substantially oppose one another, such that the terminals are in relatively close proximity over substantially the entirety of the terminals. For example, first terminal **108** and second terminal **112** are positioned between first side **102** and second side **104** and, more specifically, between first substrate **106** and second substrate **110**. Further, first terminal **108** and second terminal **112** are adjacent to one another extending along a width of power module **100**. In some embodiments, first terminal **108** and second terminal **112** extend substantially perpendicularly away from baseplate **120**, first substrate **106**, and second substrate **110**. First terminal **108** and second terminal **112** may also include respective flanges **142** that provide an area for attaching the external DC busbars thereto.

Power module **100** further includes an output terminal **144** configured to be coupled to and provide power to an electrical load (not shown). In the exemplary embodiment, output terminal **144** is an AC output terminal. Output terminal **144** is disposed in relatively close proximity to first terminal **108** and second terminal **112**. For example, output terminal **144** is positioned adjacent to first terminal **108** on first side **102** of power module **100** such that first terminal **108** is between output terminal **144** and second terminal **112**. Output terminal **144** is electrically coupled to second conductive substrate **116**. More specifically, output terminal **144** is either soldered or ultrasonically welded to second conductive substrate **116**. Additionally, output terminal **144** may be positioned adjacent to either DC bus (i.e., either first terminal **108** or second terminal **112**), or may be positioned between DC buses (i.e., sandwiched between first terminal **108** and second terminal **112**). Such positioning enables tailoring an AC to DC coupling and symmetrical path lengths. Output terminal **144** includes a first foot **146** electrically coupled to second conductive substrate **116**. Output terminal **144** includes a flange **148** to which an electrical load may be physically bolted.

In the exemplary embodiment, power module **100** may further include a third substrate **150** and a fourth substrate **152**. Third substrate **150** is positioned on first side **102** of power module **100** adjacent to first substrate **106** along a width of power module **100**. Fourth substrate **152** is positioned on second side **104** of power module **100** adjacent to second substrate **110** along the width of power module **100**.

Third substrate **150** includes identical components and functionalities as first substrate **106**, and fourth substrate **152** includes identical components and functionalities as second substrate **110**, so their descriptions are not described in detail herein. Additionally, first terminal **108** includes a second foot **154** coupled to third substrate **150**, second terminal **112** includes a second foot **156** coupled to fourth substrate **152**, and output terminal **144** includes a second foot **158** coupled to third substrate **150**, such that each terminal features a second foot with two substrates per switch structure.

The interconnection of first terminal **108**, first substrate **106** and third substrate **150**, second substrate **110** and fourth substrate **152**, and second terminal **112** forms a commutation power loop path configured to minimize loop inductance within power module **100**. More specifically, the interconnection of first terminal **108**, first conductive substrate **114**, the first plurality of power semiconductor switches **122**, second conductive substrate **116**, third conductive substrate **130**, the second plurality of power semiconductor switches **136**, and fourth conductive substrate **132**, second terminal **112**, and output terminal **144** forms the commutation power loop path. The commutation power loop path includes a source current path defined from first terminal **108** through first substrate **106** and third substrate **150**, and a return current path defined from second substrate **110** and fourth substrate **152** through second terminal **112**.

The first plurality of power semiconductor switches **122** in first substrate **106** and third substrate **150** form a first switch structure, and the second plurality of power semiconductor switches **136** in second substrate **110** and fourth substrate **152** form a second switch structure. In operation, first terminal **108**, second terminal **112**, and output terminal **144** are configured to be connected, respectively, to a positive DC busbar, a negative DC busbar, and an electrical load requiring a different voltage than that provided by the busbars. The first and second pluralities of power semiconductor switches **122**, **136** are configured to be switched between a conductive and a non-conductive state (“regulated”). By controlling a rate of regulation of the first and second pluralities of power semiconductor switches **122**, **136**, a proper output voltage for supplying the load can be provided at output terminal **144**.

In a conducting state of the first and second switch structures (i.e., in a conducting state of the first and second pluralities of power semiconductor switches **122**, **136**), current in power module **100** flows sequentially (from an external DC busbar electrically contacted with first terminal **108**) to first terminal **108**, to first conductive substrate **114** of first substrate **106** and third substrate **150** (via first foot **124** and second foot **154** of first terminal **108**), then to the drains of the first plurality of power semiconductor switches **122** of the first switch structure, and then to second conductive substrate **116** of first substrate **106** and third substrate **150** via first wire bonds **126**. The current then flows through second wire bonds **128** to third conductive substrate **130** of second substrate **110** and fourth substrate **152**, into the drains of the second plurality of power semiconductor switches **136** of the second switch structure, to fourth conductive substrate **132** via third wire bonds **138**. Next, the current flows through first foot **140** and second foot **156** into second terminal **112** (and ultimately on to another external DC busbar that electrically contacted with second terminal **112**).

During operation, it is desirable to have the current flowing through individual current loops formed through each of the first pluralities of power semiconductor switches **122** of first substrate **106** and third substrate **150** and each of the second pluralities of power semiconductor switches **136**

of second substrate **110** and fourth substrate **152** to be approximately evenly distributed. Such balance between the first and second pluralities of power semiconductor switches **122**, **136** is accomplished when an impedance through the first and second pluralities of power semiconductor switches **122**, **136** is approximately equal with respect to each other of the first and second pluralities of power semiconductor switches **122**, **136**. In the exemplary embodiment, bond wires are only formed between conductive substrates, and first terminal **108** and second terminal **112** are ultrasonically welded, soldered, brazed, or sintered to the conductive substrates to eliminate bond wire connections. Further the conductive substrates, first terminal **108**, and second terminal **112** are positioned in close physical proximity and aligned with current flowing in adjacent conductors being oppositely directed. In this manner, an electromagnetic field generated in each conductor due to the current flow will tend to cancel electromagnetic field generated in adjacent conductors having opposite current flow. Cancellation of the electromagnetic fields reduces the inductance in those conductors thereby reducing the impedance of each individual current loop. Reducing the inductance in power switching circuit **400** also improves the performance of power switching circuit **400** at very high frequency operation.

In the exemplary embodiment, power module **100** is configured to reduce the parasitic inductance for the commutation power loop path from individual power semiconductor switches devices **122**. To reduce the inductance, the current paths in and out of the module are maintained in close proximity with respect to each other so that an induced flux generated in each path when current flows through the modules are equal and opposite thus canceling each other out and reducing the overall parasitic inductance seen by the commutation power loop. To avoid spacing and separation requirements, a laminated bus structure bond wires are only formed between conductive substrates, and first terminal **108** and second terminal **112** are ultrasonically welded, soldered, brazed, or sintered to the conductive substrates to eliminate bond wire connections. Further the conductive substrates, first terminal **108**, and second terminal **112** are positioned in close physical proximity and aligned with current flowing in adjacent conductors being oppositely directed. The laminated bus structure also allows for relatively short and very consistent wire bond lengths between power semiconductor switches to further reduce the inductance and resistance of the interconnect to power module **100**.

Power module **100** provides 30%-70% lower inductance than is traditionally available in this type of design. Each of the individual substrates **106**, **110**, **150**, **152** is individually testable before implementation into a system. The goal is to minimize parasitic inductance, which is accomplished by providing a very short commutation loop between first terminal **108** and second terminal **112**. In addition, power module **100** provides reduced parasitic inductance between first terminal **108** and output terminal **144**, as well as second terminal **112** and output terminal **144**.

FIG. **4** is a perspective view of an exemplary power module **400**. FIG. **5** is a top view of power module **400**. FIG. **6** is a side view of power module **400**. In the exemplary embodiment, power module **400** includes a first side **402** and a second side **404**. First side **402** includes a first substrate **406** electrically coupled to a first terminal **408**. Second side **404** includes a second substrate **410** electrically coupled to a second terminal **412**.

First substrate **406** includes a first conductive substrate **414** and a second conductive substrate **416**. First and second

conductive substrates **414**, **416** are patterned copper layers that are disposed on a dielectric layer **418**. Dielectric layer **418** may include a ceramic tile. First substrate **406**, including first and second conductive substrates **414**, **416** coupled to dielectric layer **418** forms a power electronic substrate, such as a direct bonded copper (DBC) substrate. First substrate **406** is disposed on a substantially planar baseplate **420**.

First conductive substrate **414** includes a first plurality of power semiconductor switches **422** arranged thereon. For example, in the exemplary embodiment, the first plurality of power semiconductor switches **422** includes metal-oxide semiconductor field-effect transistors (MOSFET). Alternatively, the first plurality of power semiconductor switches **422** may include insulated gate bipolar transistors (IGBT), junction gate field-effect transistors (JFET), bipolar junction transistors (BJT), or a diode. The first plurality of power semiconductor switches **422** may be formed of semiconducting material, such as, for example, silicon, silicon carbide (SiC), Aluminum nitride (AlN), Gallium nitride (GaN), or Boron nitride (BN). In the exemplary embodiment, first conductive substrate **414** includes four power semiconductor switches **422** arranged thereon; however, first conductive substrate **414** may include any number of power semiconductor switches that enables power module **400** to function as described herein.

First conductive substrate **414** includes a T-shaped first conductive substrate having a base portion **424** and a top portion **426**. Each of the first plurality of power semiconductor switches **422** is arranged on top portion **426**. More specifically, each of the first plurality of power semiconductor switches **422** includes a drain terminal electrically coupled to top portion **426** and is coupled to first terminal **408** via first conductive substrate **414**. First terminal **408** is electrically coupled to base portion **424**. First terminal **408** is one of soldered or ultrasonically welded to first conductive substrate **414** to form the electrical connection therebetween. First terminal **408** includes a first foot **428** extending therefrom that electrically coupled to first conductive substrate **414**.

Each of the first plurality of power semiconductor switches **422** also includes a source terminal electrically coupled to second conductive substrate **416** using a first wire bond **430**. That is, each of the first plurality of power semiconductor switches **422** has the source connection on a top side of the switch. First wire bond **430** is coupled to the top side of the switch to couple the source terminal to second conductive substrate **416**. Thus, first conductive substrate **414** is electrically coupled to second conductive substrate **416** via the first plurality of power semiconductor switches **422** and first wire bonds **430**.

Second conductive substrate **416** is electrically coupled to first wire bonds **430** to form the electrical connection with first conductive substrate **414**. Second conductive substrate **416** is also electrically coupled to second wire bond **432** to form an electrical connection with second side **404** of power module **400**.

In the exemplary embodiment, second conductive substrate **416** includes an inner second conductive substrate **434** positioned on an inner side of base portion **424**, and an outer second conductive substrate **436** positioned on a second side **404** of base portion **424**. Inner second conductive substrate **434** and outer second conductive substrate **436** are coupled to the same number of the first plurality of power semiconductor switches **422** to provide symmetrical, dynamic current distribution across the first plurality of power semiconductor switches **422**.

Current flowing from first terminal **408** flows into first conductive substrate **414**, through the drain terminal of each of the first plurality of power semiconductor switches **422**, through the source terminal of each of the first plurality of power semiconductor switches **422**, through first wire bonds **430**, into inner second conductive substrate **434** and outer second conductive substrate **436**, and then to second side **404** via second wire bonds **432**.

Second substrate **410** includes a third conductive substrate **438** and a fourth conductive substrate **440**. Third and fourth conductive substrates **438**, **440** are patterned copper layers that are disposed on a dielectric layer **442**. Dielectric layer **442** may include a ceramic tile. Second substrate **410**, including third and fourth conductive substrates **438**, **440** coupled to dielectric layer **442** forms a power electronic substrate, such as a direct bonded copper (DBC) substrate. Second substrate **410** is disposed on substantially planar baseplate **420**.

Third conductive substrate **438** includes a second plurality of power semiconductor switches **444** arranged thereon. For example, in the exemplary embodiment, the second plurality of power semiconductor switches **444** includes metal-oxide semiconductor field-effect transistors (MOSFET). Alternatively, the second plurality of power semiconductor switches **444** may include insulated gate bipolar transistors (IGBT), junction gate field-effect transistors (JFET), bipolar junction transistors (BJT), or a diode. The second plurality of power semiconductor switches **444** may be formed of semiconducting material, such as, for example, silicon, silicon carbide (SiC), Aluminum nitride (AlN), Gallium nitride (GaN), or Boron nitride (BN). In the exemplary embodiment, third conductive substrate **438** includes four power semiconductor switches **444** arranged thereon; however, third conductive substrate **438** may include any number of power semiconductor switches that enables power module **400** to function as described herein.

Third conductive substrate **438** includes a T-shaped third conductive substrate having a base portion **446** and a top portion **448**. Each of the second plurality of power semiconductor switches **444** is arranged on top portion **448**. More specifically, each of the second plurality of power semiconductor switches **444** includes a drain terminal electrically coupled to top portion **448** and is coupled to second conductive substrate **416** via third conductive substrate **438**. The electrical connection of the drain terminal to third conductive substrate **438** enables each of the second plurality of power semiconductor switches **444** to receive current flowing from second conductive substrate **416** to third conductive substrate **438** via second wire bond **432**.

Each of the second plurality of power semiconductor switches **444** also includes a source terminal electrically coupled to fourth conductive substrate **440** using a third wire bond **448**. That is, each of the second plurality of power semiconductor switches **444** has the source connection on a top side of the switch. Third wire bond **448** is coupled to the top side of the switch to couple the source terminal to fourth conductive substrate **440**. Thus, fourth conductive substrate **440** is electrically coupled to third conductive substrate **438** via the second plurality of power semiconductor switches **444** and third wire bonds **448**.

Fourth conductive substrate **440** is electrically coupled to third conductive substrate **438** as well as to second terminal **412**. Second terminal **412** is one of soldered and ultrasonically welded to fourth conductive substrate **440** to form the electrical connection therebetween. Second terminal **412**

includes a first foot **450** and a second foot **452** extending therefrom that electrically coupled to fourth conductive substrate **440**.

In the exemplary embodiment, fourth conductive substrate **440** includes an inner fourth conductive substrate **454** positioned on an inner side of base portion **446**, and an outer fourth conductive substrate **456** positioned on an outer side of base portion **446**. Inner fourth conductive substrate **454** and outer fourth conductive substrate **456** are coupled to the same number of the second plurality of power semiconductor switches **444** to provide symmetrical, dynamic current distribution across the second plurality of power semiconductor switches **444**.

Current flowing from second conductive substrate **416** flows through second wire bonds **432** into third conductive substrate **438**, through the drain terminal of each of the second plurality of power semiconductor switches **444**, then through the source terminal of each of the second plurality of power semiconductor switches **444**, through third wire bonds **448** into inner fourth conductive substrate **454** and outer fourth conductive substrate **456**, and into second terminal via first foot **450** and second foot **452**.

In the exemplary embodiment, first terminal **408** is a positive DC terminal and second terminal **412** is a negative DC terminal. First terminal **408** and second terminal **412** are configured to be coupled to positive and negative busbars (not shown), respectively. The “positive” and “negative” DC terminals and/or busbars are at different electric potentials relative to one another during operation, but are not restricted to a specific polarity. In the exemplary embodiment, first terminal **408** and second terminal **412** substantially oppose one another, such that the terminals are in relatively close proximity over substantially the entirety of the terminals. For example, first terminal **408** and second terminal **412** are positioned between first side **402** and second side **404** and, more specifically, between first substrate **406** and second substrate **410**. Further, first terminal **408** and second terminal **412** are adjacent to one another extending along a width of power module **400**. In some embodiments, first terminal **408** and second terminal **412** extend substantially perpendicularly away from baseplate **420**, first substrate **406**, and second substrate **410**. First terminal **408** and second terminal **412** may also include respective flanges **458** that provide an area for bonding thereto.

Power module **400** further includes an output terminal **460** configured to be coupled to and provide power to an electrical load (not shown). In the exemplary embodiment, output terminal **460** is an AC output terminal **460**. Output terminal **460** is disposed in relatively close proximity to first terminal **408** and second terminal **412**. For example, output terminal **460** is positioned adjacent to first terminal **408** on first side **402** of power module **400** such that first terminal **408** is between output terminal **460** and second terminal **412**. Output terminal **460** is electrically coupled to second conductive substrate **416**. More specifically, output terminal **460** is one of soldered or ultrasonically welded to third conductive substrate **438** and is electrically coupled to second conductive substrate **416** via second bond wire **432**. Additionally, output terminal **460** may be positioned adjacent to a single DC bus (i.e., either first terminal **408** or second terminal **412**), or may be positioned between DC buses (i.e., between first terminal **408** and second terminal **412**). Such positioning enables tailoring an AC to DC coupling and symmetrical path lengths. Output terminal **460** includes a first foot **462** electrically coupled to third conductive sub-

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strate 438. Output terminal 460 includes a flange 464 to which the port of an electrical load may be physically bolted.

In the exemplary embodiment, power module 400 may further include a third substrate 466 and a fourth substrate 468. Third substrate 466 is positioned on first side 402 of power module 400 adjacent to first substrate 406 along a width of power module 400. Fourth substrate 468 is positioned on second side 404 of power module 400 adjacent to second substrate 410 along the width of power module 400. Third substrate 466 includes identical components and functionalities as first substrate 406, and fourth substrate 468 includes identical components and functionalities as second substrate 410, so their descriptions are not described in detail herein.

Power module 400 provides similar advantages as those provided by power module 100 (shown in FIG. 1). Additionally, power module 400 provides improved symmetry of the first and second pluralities of power semiconductor switches 422, 444 such that current flowing through each of the switches travels substantially the same distance and along substantially the same individual current paths. Such symmetry enables equal current distribution among the switches as well as simultaneous control of the timing of the switches.

FIG. 7 is a perspective view of an exemplary power module 700. FIG. 8 is a top view of power module 700. FIG. 9 is a side view of power module 700. Power module 700 is similar to power module 100 (shown in FIGS. 1-3). Accordingly, components of power module 700 that are the same as power module 100 are identified in FIGS. 7-9 using the same reference characters used in FIGS. 1-3, and their description will not be repeated.

In the exemplary embodiment, power module 700 includes first terminal 108 and second terminal 112, and further includes two output terminals, a first output terminal 702 and a second output terminal 704. First and second terminals 108, 112 are positioned adjacent to one another, first output terminal 702 is positioned adjacent to a side of first terminal 108 that is opposite the side adjacent to second terminal 112, and second output terminal 704 is positioned adjacent to a side of second terminal 112 that is opposite the side adjacent to first terminal 108.

In one embodiment, first output terminal 702 and second output terminal 704 are configured or "tied" together either internally within power module 700 or externally outside power module 700. Tying first and second output terminals 702, 704 together forms a similar half-bridge configuration to that described above with respect to FIGS. 1-3. Additionally, the half-bridge configuration facilitates reducing the inductance in the DC+ to DC- loop (i.e., from first terminal 108 to second terminal 112) with close proximity.

In another embodiment, rather than tying them together, first output terminal 702 and second output terminal 704 are separated to enable power module 700 to accommodate two independent low-inductance switches. For example, a first low-inductance switch is formed by tightly coupling first terminal 108 and first output terminal 702, and a second low-inductance switch is formed by tightly coupling second terminal 112 and second output terminal 704. The tight coupling of the AC to DC for both the first and second low-inductance switches facilitates reducing inductance for more complicated electrical topologies where this inductance is also critical.

In an alternative embodiment, similarly to FIGS. 1-3, power module 700 may include only a single output terminal 146. In such an embodiment, the substrates would be either wire bonded or ribbon bonded together.

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In the exemplary embodiment, first terminal 108, second terminal 112, first output terminal 702, and second output terminal 704 are either wire bonded or ribbon bonded together their respective conductive substrates. The wire bonding or ribbon bonding facilitates providing increased flexibility in the design and additional options for manufacturing and mechanical stress relief.

In the exemplary embodiment, power module 700 includes first plurality of semiconductor switches 122 and second plurality of semiconductor switches 136. Power module 700 also includes a diode 706 coupled in series with each first semiconductor switch 122 and each second semiconductor switch 136. Specifically, diode 706 is coupled in series between each first semiconductor switch 122 and first output terminal 702. Further, diode 706 is coupled in series between second output terminal 704 and second terminal 112. In the exemplary embodiment, first and second semiconductor switches 122, 136 are MOSFETs and diodes 706 are freewheeling diodes; however, first and second semiconductor switches 122, 136 and diodes 706 may be any other similar device that enables power module 700 to function as described herein. Coupling diodes 706 in series with first and second semiconductor switches 122, 136 creates a much larger footprint, which leads more to the scalability of this style approach, while still maintaining the independently testable substrates prior to full assembly commitment.

FIG. 10 is a flow chart of an exemplary method 1000 of forming power module devices 100, 400, and 700 (shown in FIGS. 1-3, FIGS. 4-6, and FIGS. 7-9, respectively). In the exemplary embodiment, method 1000 includes providing 1002 a first conductive substrate on a first substrate, arranging 1004 a first plurality of power semiconductor switches on the first conductive substrate, and electrically coupling 1006 the first conductive substrate to a first terminal and to at least one second conductive substrate. Method 1000 also includes providing 1008 a third conductive substrate on a second substrate, arranging 1010 a second plurality of power semiconductor switches on the third conductive substrate, and electrically coupling 1012 the third conductive substrate to the second conductive substrate and to at least one fourth conductive substrate. Method 1000 further includes electrically coupling 1014 the fourth conductive substrate to a second terminal.

FIG. 11 is a perspective view of an exemplary power module 1100. FIG. 12 is a top view of power module 1100. FIG. 13 is a side view of power module 1100. Power module 1100 is similar to power module 100 (shown in FIGS. 1-3). Accordingly, components of power module 1100 that are the same as power module 100 are identified in FIGS. 11-13 using the same reference characters used in FIGS. 1-3, and their description will not be repeated. The only difference between power module 1100 of FIGS. 11-13 and power module 100 of FIGS. 1-3 is the configuration of first terminal 108, second terminal 144, and output terminal 112.

In the exemplary embodiment, first terminal 108 and second terminal 144 are tightly coupled and extend along a width of power module 100. First terminal 108 and second terminal 144 are biased towards first side 102 of power module 1100 and, accordingly, extend substantially perpendicularly away from first substrate 106 and third substrate 150.

Output terminal 112 is not positioned adjacent to or tightly coupled with first terminal 108 or second terminal 144. Rather, output terminal 112 extends across only a portion of the width of power module 1100. Additionally, output terminal 112 is biased towards second side 104 of

power module **1100** and, accordingly, extends substantially perpendicularly away from second substrate **110** and fourth substrate **152**.

The orientation of first terminal **108**, second terminal **144**, and output terminal **112** is such that they are in-line with power module **1100** and match a standard industry footprint, while also achieving the same low-inductance advantages as power module **100**.

A technical advantage of power modules **100**, **400** is lower parasitic inductance, which results in a higher operating frequency capability, reduced losses, and higher voltage margin. Any wire bonding is located only on conductive substrates and connection to power terminals is achieved using ultrasonic welding. This enables individual testing of each substrate as well as provides shorter commutation loops, resulting in increased efficiency and lower inductance within power modules **100**, **400**.

Exemplary embodiments of methods, systems, and apparatus for reducing loop inductance in power switching circuits are not limited to the specific embodiments described herein, but rather, components of systems and/or steps of the methods may be utilized independently and separately from other components and/or steps described herein. For example, the methods may also be used in combination with other systems requiring reduced circuit inductance and the associated methods, and are not limited to practice with only the power inverters, switching modules, and methods as described herein. Rather, the exemplary embodiment can be implemented and utilized in connection with many other applications, equipment, and systems that may benefit from reduced circuit reactance.

Although specific features of various embodiments of the disclosure may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the disclosure, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

This written description uses examples to disclose the embodiments, including the best mode, and also to enable any person skilled in the art to practice the embodiments, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. A power module comprising:

a first substrate comprising:

a first conductive substrate having a first plurality of power semiconductor switches arranged thereon; and

at least one second conductive substrate electrically coupled to said first conductive substrate;

a first terminal electrically coupled to said first conductive substrate;

a second substrate comprising:

a third conductive substrate having a second plurality of power semiconductor switches arranged thereon, said third conductive substrate electrically coupled to said second conductive substrate; and

at least one fourth conductive substrate electrically coupled to said third conductive substrate; and

a second terminal electrically coupled to said fourth conductive substrate.

2. The power module according to claim **1**, wherein said first terminal, said first substrate, said second substrate, and said second terminal form a common circuit loop configured to minimize commutation loop inductance within said power module.

3. The power module according to claim **1**, wherein said first terminal is one of soldered, brazed, sintered, ultrasonically welded, ribbon bonded, and planar interconnected to said first conductive substrate.

4. The power module according to claim **1**, wherein said second terminal is one of soldered, brazed, sintered, ultrasonically welded, ribbon bonded, and planar interconnected to said fourth conductive substrate.

5. The power module according to claim **1**, wherein each of said first plurality of power semiconductor switches comprises a drain terminal electrically coupled to said first terminal via said first conductive substrate.

6. The power module according to claim **1**, wherein each of said second plurality of power semiconductor switches comprises a drain terminal electrically coupled to said second conductive substrate via said third conductive substrate.

7. The power module according to claim **1**, wherein each of said first plurality of power semiconductor switches comprises a source terminal electrically coupled to said second conductive substrate using a wire bond.

8. The power module according to claim **1**, wherein each of said second plurality of power semiconductor switches comprises a source terminal electrically coupled to said fourth conductive substrate using a wire bond.

9. The power module according to claim **1**, wherein said first terminal comprises a positive DC terminal and said second terminal comprises a negative DC terminal.

10. The power module according to claim **1**, further comprising an output terminal electrically coupled to said second conductive substrate.

11. The power module according to claim **10**, wherein said output terminal is one of soldered, brazed, sintered, ultrasonically welded, ribbon bonded, and planar interconnected to said third conductive substrate and is electrically coupled to said second conductive substrate using one of a bond wire and a ribbon bond.

12. The power module according to claim **10**, wherein said output terminal is one of soldered, brazed, sintered, ultrasonically welded, ribbon bonded, and planar interconnected to said second conductive substrate.

13. The power module according to claim **10**, wherein said output terminal comprises:

a first output terminal coupled to said second conductive substrate; and

a second output terminal coupled to said third conductive substrate,

wherein said first terminal and said second terminal are positioned between said first output terminal and said second output terminal.

14. The power module according to claim **1**, wherein said first conductive substrate and said third conductive substrate each comprise a T-shaped conductive substrate having a base portion and a top portion.

15. The power module according to claim **14**, wherein: said first plurality of power semiconductor switches are arranged on said top portion of said first conductive substrate;

said first terminal is electrically coupled to said base portion of said first conductive substrate;

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said second conductive substrate is electrically coupled to said base portion of said third conductive substrate; and said second plurality of power semiconductor switches are arranged on said top portion of said third conductive substrate.

16. The power module according to claim **15**, wherein said second conductive substrate and said fourth conductive substrate each comprise:

an inner second conductive substrate positioned on a first side of said base portion; and

an outer second conductive substrate positioned on a second side of said base portion, the second side opposite from the first side.

17. A method of forming a power module, comprising: providing a first conductive substrate on a first substrate; arranging a first plurality of power semiconductor switches on the first conductive substrate;

electrically coupling the first conductive substrate to a first terminal and to at least one second conductive substrate;

providing a third conductive substrate on a second substrate;

arranging a second plurality of power semiconductor switches on the third conductive substrate;

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electrically coupling the third conductive substrate to the second conductive substrate and to at least one fourth conductive substrate; and electrically coupling the fourth conductive substrate to a second terminal.

18. The method according to claim **17**, wherein: electrically coupling the first conductive substrate to the first terminal comprises one of soldering, brazing, sintering, ultrasonically welding, ribbon bonding, and planar interconnecting the first conductive substrate to the first terminal; and

electrically coupling the fourth conductive substrate to the second terminal comprises one of soldering, brazing, sintering, ultrasonically welding, ribbon bonding, and planar interconnecting the fourth conductive substrate to the second terminal.

19. The method according to claim **16**, further comprising electrically coupling an output terminal to the second conductive substrate.

20. The method according to claim **16**, wherein said first conductive substrate and said third conductive substrate each comprise a T-shaped conductive substrate having a base portion and a top portion.

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